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(NASA-CR-159680) CONCEPTS FOR 18/30 GHz SATELLITE COMMUNICATION SYSTEM STUDY. EXECUTIVE SUMMARY (Ford Aerospace and Communications Corp.) 36 p HC A03/MF A01 CSCL 17B G3/32

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CONCEPTS FOR 18/30 GHz SATELLITE COMMUNICATION SYSTEM STUDY

EXECUTIVE SUMMARY

Contract NAS3-21362

Prepared for:
NASA LEWIS RESEARCH CENTER
Cleveland, Ohio

Ford Aerospace &
Communications Corporation
Engineering Services Division

3939 Fabian Way
Palo Alto, California 94303

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INTRODUCTION

This Executive Summary highlights the study report on concepts for 18/30 GHz satellite communications systems prepared by the Western Development Laboratories (WDL) Division of Ford Aerospace & Communications Corporation (FACC) in Palo Alto, California under contract NAS3-21362 to NASA/Lewis Research Center. The effort was initiated in May 1978. The principal FACC contributors are R. Jorasch, M. Baker, R. Davies, L. Cuccia, and Dr. C. Mitchell. The analysis of rain attenuation effects was prepared under subcontract by Future Systems, Inc., R. Stamminger and J. Stein.

This summary is organized into the following sections:

1.0 STUDY OBJECTIVES

The objective of the study report was to define and evaluate future satellite communications concepts that utilize the K_A-band (18 GHz downlink, 30 GHz uplink) transmission frequencies. It is anticipated that within 10 to 15 years the current satcom links at C-band (4/6 GHz) and K_U-band (11/14 GHz) may be fully utilized. It is also anticipated that new wideband data transmission requirements, such as teleconferencing, may create a further expansion of current data transmission requirements. The study report outlines the potential application of the wide-bandwidth (2.5 GHz) K_A-band links for fixed service communications via satellite within the United States.

The study was structured as shown in Table 1 to provide information for resolving the following questions:

- Will 18/30 GHz satellite trunking into major terminals be competitive with present and future communication alternatives (such as buried waveguide, optical fiber, and satellites)? What are the probable methods of implementing this service?
- Could 18/30 GHz satellite systems provide economical services directly to the users, that is, via small inexpensive earth terminals? What are the probable methods of implementing such a service?
- What are the advanced technology efforts that need to be carried out to reduce the commercial risk of introducing such a communication system?
- What is the impact of rain attenuation on the technical and economical viability of 18/30 GHz systems, and what are the likely methods of minimizing this problem?
- What are the ultimate cost-effective capacities of the 18/30 GHz bands for domestic fixed service, given current and planned technology?

Table 1. 18/30 GHz Satcom Configuration Study Tasks

- Evaluate major terminal trunking configurations
  - 99.9% communications availability
  - 200 MHz interconnect of 10 to 40 trunking sites
  - Multiple spot beam antenna
- Evaluate direct-to-user configuration
  - 99.5% communications availability
  - 25-40 antenna beams forming full CONUS coverage
- Determine critical technologies to support millimeter wave satellite communications in period of 1985-2000

This report presents concepts rather than an optimized design. It is expected that an optimized configuration would be determined at a later date after communications requirements are fixed and after technology developments and on-orbit tests are completed. The matrix of candidate system configurations (Figure 1) becomes very large if each of the parameters is variable. Key decisions include number of spacecraft antenna beams, communications modulation technique, use of switching and/or processing in the spacecraft, propagation availability level, data quality, flexibility for future expansion, use of space diversity earth terminals, etc.

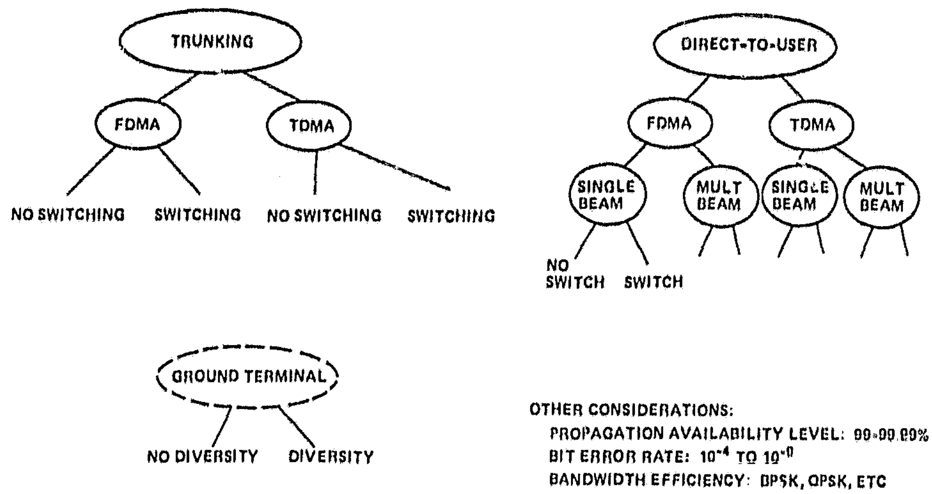


Figure 1. Matrix of Candidate System Configurations

Two types of systems were examined for both TDMA and FDMA methods of operation. The first is a trunking system utilizing spot beams from the spacecraft (0.3° halfpower beamwidth) to illuminate 10 to 40 fixed terminal locations within CONUS. An interconnect capacity of 200 MHz is required among all terminal pairs, with a target goal of 99.9% communications availability. Earth terminals of 12 meter diameter were used in tandem at a separation of about 8 km or more in order to achieve diversity to minmize the impact of heavy rainfall attenuation. The total spacecraft data throughput capacity is 25 Gb/s for baseline design. The second system provides complete coverage of CONUS with an overlapping set of 25 separate beams, each of about 1° halfpower beamwidth. The number of earth terminals ranges from 1,000 to 10,000 and they are located in close proximity to the user location. Requirements include a design goal of at least 99.5% communications availability. A baseline user antenna diameter of 4.5 meters is forecast.

The study approach used by FACC is outlined in Figure 2. A baseline for both trunking and DTU systems was defined, and detailed analysis was performed on the baseline to provide a comprehensive framework for consideration of all variables. Alternatives to the baseline are presented to permit tradeoff comparisons.

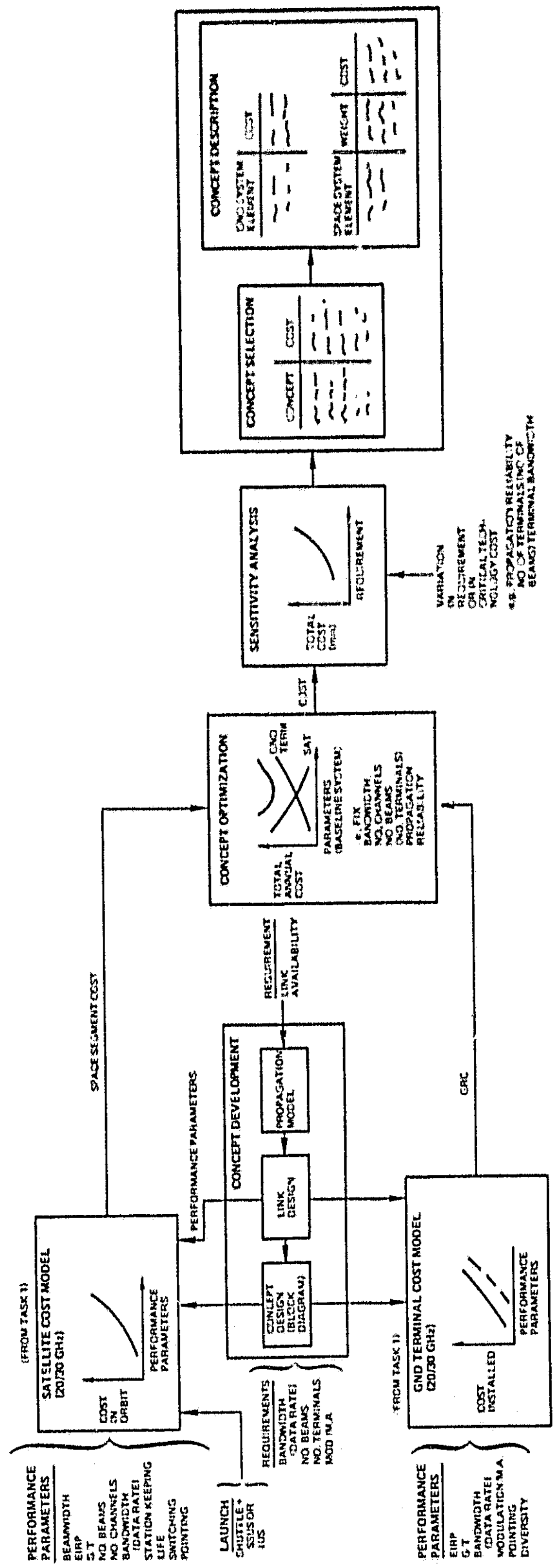


Figure 2. Approach to System Concept Definition

2.0 CONCLUSIONS AND RECOMMENDATIONS

The study evaluated and defined concepts for satellite communication systems at the 18/30 GHz transmission bands. The broad scope of the study required examination of a multiplicity of interconnected parameters ranging from specific technology details to total system economic costs.

It was determined that K_A band systems will incur a small communications outage during very heavy rainfall periods and that reducing the outage to zero would lead to prohibitive system costs. On the other hand, the economics of scale, ie, one spacecraft accommodating 2.5 GHz of bandwidth coupled with multiple beam frequency reuse, leads to very low costs for those users who can tolerate the 5 to 50 hours per year of downtime. It is postulated that a multiple frequency band (C-band, K_U-band, K_A-band) satellite network will provide the ultimate optimized match to the consumer performance/economics demands.

General recommendations and conclusions reached by the Ford Aerospace & Communications Corporation study team are summarized in the categories of (1) technology, (2) trunking systems, (3) direct-to-user systems, and (4) future effort.

Technology

An assessment of the 18/30 GHz technology leads to the following recommendations and conclusions:

a. It is not expected that the technology development will present a major hurdle to a successful first generation satellite communication system. No major inventions need be scheduled.

b. A more sophisticated technology than that presented in the baseline trunking and direct-to-user system design is available (or could be developed); however, it is not required for the first generation system. The emphasis in technology should focus on 10-year on-orbit reliability to meet practical user data requirements.

c. Other countries have already been developing 18/30 GHz equipment, and the United States may lose the technology lead in this frequency band. The Japanese CS satellite, with capacity of 600 Mb/s at 18/30 GHz, was launched in December 1977 and experimental tests have continued to date.

d. Spectrum conservation will become even more important in future systems, hence spectrum-efficient QPSK modulation should be used. Also the use of narrow beam antennas will permit frequency reuse several times over for CONUS coverage.

e. There is need for a current development test program to assure long term reliability at high performance and to reduce the risk associated with fixed price bidding of the spacecraft segment. Key development items should include the following:

1. Spot beam spacecraft antennas
2. CONUS coverage spacecraft antennas with multiple beams
3. High power spacecraft TWT amplifiers up to 100 W rf output
4. Solid-state spacecraft amplifiers up to 5 W rf output
5. Lightweight, broadband, multichannel filters
6. Baseband and IF switching for spacecraft
7. Diversity earth terminal implementation techniques
8. Low cost techniques for production of direct-to-user earth terminals

Trunking Systems

A review of trunking systems, which are designed to accommodate large amounts of data from a relatively small number of terminals, leads to the following:

a. The total 10-year costs of developing, manufacturing, and operating a satellite trunking system of 25 Gb/s capacity among 10 earth terminal sites within CONUS is expected to range from $365 million for a TDMA configuration to $424 million for an FDMA configuration.

b. About two-thirds of the system cost is required by the satellite segment and one-third for the terminal segment (for a 10-site network); hence performance/cost optimization of the satellite segment is of key importance.

c. It is impossible to determine an optimum trunking configuration until decisions are reached on a large number of technical, economic, political, and user demand factors. Included are communications demand growth as a function of quality and circuit availability, scenarios for determining which companies will be permitted to operate and how to share the satellite network, and desirability of large multifrequency-band satellites versus smaller satellites operating at a single frequency band.

d. An initial system configuration which is to accommodate about 16 or fewer trunking sites is better served by using an FDMA modulation technique. Elimination of the need for onboard switching is expected to enhance long term reliability.

e. If the number of trunking sites is greater than about 16, then the TDMA modulation technique becomes more attractive because of the larger filter network associated with FDMA operation. The filter network for FDMA increases as the square of the number of sites.

f. The earth terminal antennas should be limited to about 12 m in diameter. A diversity terminal, separated by 8 km or more from a main terminal, should be incorporated at each site to minimize the impact of rain outage.

g. A spot beam spacecraft antenna of 0.3° half-power beamwidth appears feasible for coverage over the extremity of CONUS. A three-axis spacecraft design is recommended in order to minimize antenna pointing errors.

h. It is technically possible to accommodate 30 to 50 spot beams from the spacecraft provided that they are spaced no closer than about 0.3° with respect to the spacecraft view angle. A resolution of New York City and Washington, D.C. on separate beams represents the limit of a 14 ft diameter spacecraft antenna.

i. The spacecraft antenna should be a dual reflector type and fit within the payload bay of the Space Shuttle Orbiter such that on-orbit unfurling is not required.

j. The spacecraft transponder channel bandwidths of the baseline design should be modified to match the skewed traffic demand model in order to maximize communications efficiency.

k. An increase in the baseline spacecraft power amplifier output to a range of 2 to 4 W rf per channel is cost effective provided that solid-state amplifier technology is available at the higher power level.

l. The costs of the satcom trunking system of this report do not include the "tail circuit" costs of getting from the terminal to the ultimate user. A greater analysis of the distribution costs is required before total circuit costs can be established.

m. It is expected that maximum capacity use would result in a satellite and terminal allocated circuit cost of $3600 per year for a 1.5 Mb/s simplex channel.

Direct-to-User Systems

A review of direct-to-user (DTU) systems, which are designed to accommodate up to several megabits of data per second from a very large number of small user terminals (1000 to 10,000), leads to the following recommendations and conclusions:

a. The total 10-year cost of developing, manufacturing, and operating a satellite DTU system of 3.5 Gb/s capacity among 1000 user terminals located within CONUS is expected to range from $1.230 billion for a TDMA configuration to $1.555 billion for an FDMA configuration.

b. The TDMA systems are more attractive for a large number of users (ie, more than 500) whereas the FDMA systems are economically more viable for a low number of users. The DTU systems are expected to contain as many as 10,000 terminals; hence the TDMA communications technique is recommended.

c. Based on a 1000 terminal network, about three-fourths of the system cost is required by the terminal segment and one-fourth for the satellite segment. Thus performance/cost optimization of the terminal is of key importance.

d. It is expected that a TDMA terminal will cost about $518,000 and that an FDMA terminal will cost $668,000. These terminals could simultaneously accommodate 10 channels at 64 kb/s, one channel at 1.5 Mb/s, and one channel at 6.3 Mb/s.

e. It is recommended that user terminal antennas not exceed 5 meters in diameter in order to maintain low cost manufacture and installation. A variable power transmitter reduces the outage period associated with heavy rainfall.

f. An increase of spacecraft power from that of the baseline design is not cost effective because the communications is uplink limited; more spacecraft power only helps the downlink.

g. Techniques to provide a variable link capacity per coverage beam are recommended in order to effectively match the consumer traffic demands. Variations to modify the equal capacity baseline concept include variable baseband switch interconnect time, nonuniform burst rate per beam, and allocation of additional transponder channels to the high user density beams.

h. A 25-beam spacecraft that provides overlapping coverage of all of CONUS is feasible. Baseline spacecraft power of 25 W rf per beam leads to spacecraft configurations that will require about one-third the length of the Shuttle Orbiter payload bay.

i. Demodulation to baseband, baseband switching at a nominal rate of 750 reconfigurations per second, and remodulation in the spacecraft are recommended in order to enhance link performance and remove the need for sophisticated onboard frequency synthesizers.

j. The allocated circuit costs of DTU service are dependent upon many assumptions concerning costs of financing, inflation rates, circuit fill factors, etc. One estimate of the costs (neglecting inflation) for a full capacity system is $3700 per year per 64 kb/s channel, $74,000 per year for a 1.5 Mb/s channel, and $307,000 per year for a 6.3 Mb/s channel. However, these costs are not to be construed as projected tariffs.

Continued Effort

This report evaluates some of the system concepts and the general economic feasibility of 18/30 GHz satcom operation. Recommendations concerning follow-on technology development, continued system studies, and experimental programs are as follows:

a. The matrix of potential operational concepts for satcom systems contains many interconnected paths, as shown in Figure 1.3-1. This report has focused on single-service satellites with uniform traffic demand with emphasis as shown by shading of the figure. It is recommended that the concept analysis phase be continued and expanded to include:

1. Analysis of combined trunking and DTU service from a single spacecraft.
2. Hybrid satellites that have cross-connected transponders for operation at C-band, K_U-band, and K_A-band.
3. Multiple on-orbit satellite configurations such that several communications carriers may share in accommodating user demand.
4. Additional in-depth analysis of satcom configurations to meet specific communications network requirements.
5. Studies of consumer demand as function of outage and relative circuit costs.
6. Additional study of rain attenuation and diversity techniques using data currently collected on U.S. and Japan space programs.
7. A more detailed examination of spares, operations, and onsite terminal maintenance because of significant system cost impact.

b. The key technology developments have been previously identified. It is recommended that the hardware development program, as currently planned by NASA/Lewis Research Center, be implemented. Additional developments may be required as the study efforts focus on specific design configurations.

c. To verify the critical technology items it is recommended that a Phase II On-Orbit Experimental Test Program be implemented. This will permit evaluation of multiple-spot-beam antenna performance, frequency reuse through spatial and polarization diversity, and outage control during heavy rain periods.

3.0 TRUNKING SYSTEMS

The trunking type of satellite communications system at 18/30 GHz is designed to accommodate very high data rates among a relatively small number of earth terminals (10 to 40), which may be located anywhere within the continental United States (CONUS) excluding Alaska. The main distinction of this type of configuration is that the user terrestrial network distribution ("tails circuit") costs are higher than that of direct-to-user systems because of the widely spaced terminal locations. For trunking systems the total cost of the spacecraft segment generally exceeds that of the terminal segment and hence it becomes important to optimize the performance/cost relationship for the spacecraft design.

The general configuration of the baseline trunking system is shown in Figure 3. Ten spot beams from a geosynchronous orbit satellite illuminate the network of 10 selected trunking site locations. The spacecraft antenna technology for multiple spot beams permits up to about 50 beams; however, the physical constraints on feed layout and interbeam isolation requirements will limit the number of spot beams in the highly concentrated demand areas.

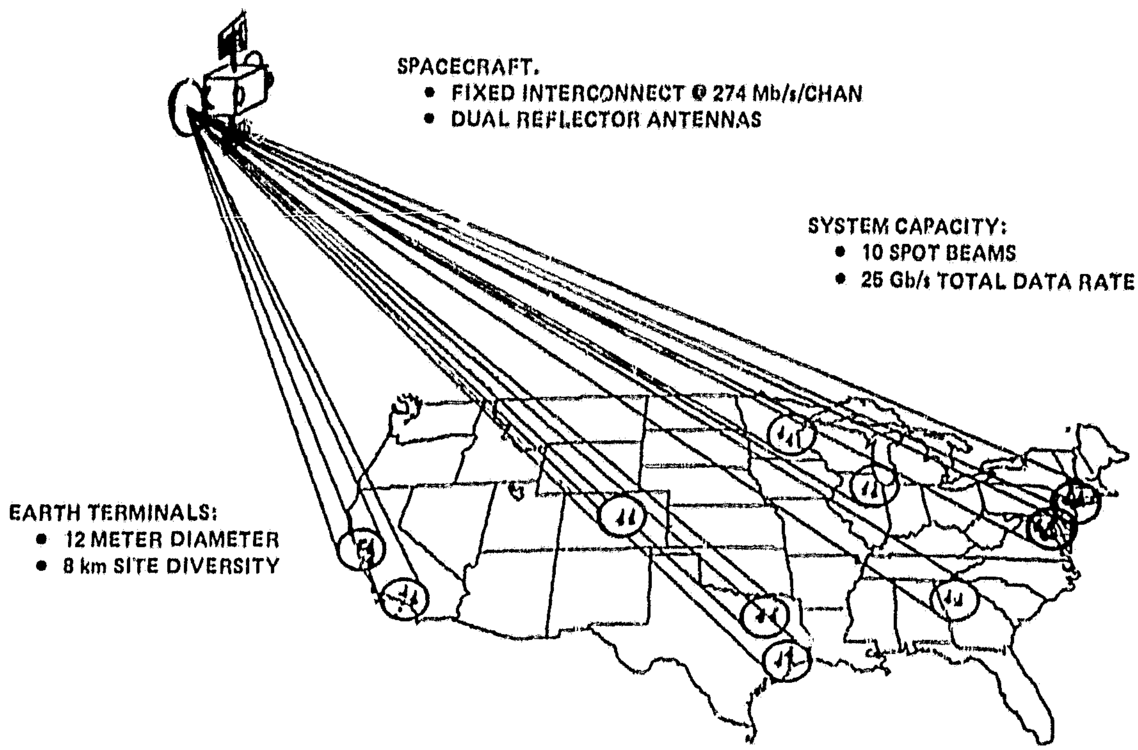


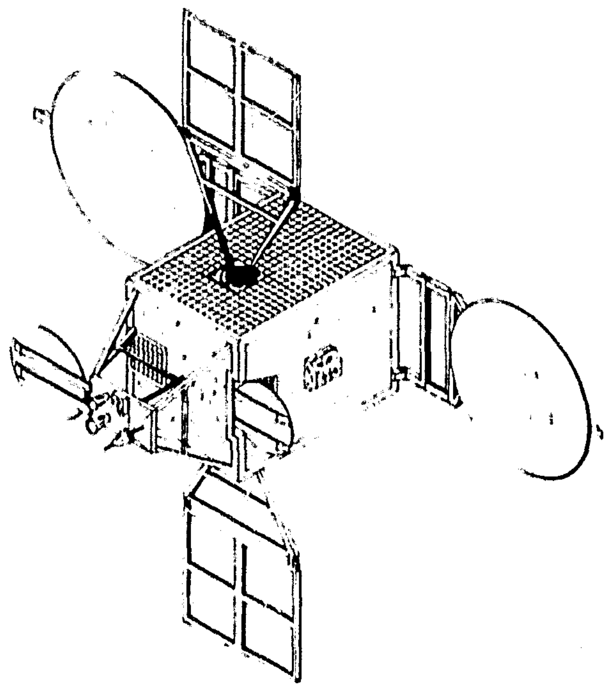
Figure 3. Trunking Network Configuration

Trunking Spacecraft

The baseline spacecraft (Figure 4) is three-axis stabilized and uses a dual reflector antenna to achieve the spot beam coverage. A full interconnect of 274 Mb/s is provided between all trunking terminals, which leads to a maximum data throughput capacity of 25 Gb/s. The baseline approach uses frequency division multiple access (FDMA) communications, and quadriphase modulation (QPSK) is used for spectrum efficiency. CONUS spot beam coverage is obtained with a dual reflector spacecraft antenna at 18 GHz and a separate antenna for 30 GHz. A lens type antenna and large unfurlable antennas provide other design alternatives.

For the baseline it is assumed that all of the spot beams are equal in size (about 0.3° half power beamwidth) and that the EIRP and G/T presented to any point within CONUS are equal. An equal data capacity per beam is also assumed. It is recognized that any optimized system configuration should match the real user distribution as much as possible.

The design of the spacecraft is compatible with Shuttle launch.



ON-ORBIT WEIGHT	2420 lb
LENGTH	21 ft
MAXIMUM ARRAY POWER	1140 W
RF POWER	1 W/CHAN
ANTENNA	10 BEAMS, 0.3°
PERIGEE MOTOR	SPM-4
UNIT SPACECRAFT COST	$27 M

Figure 4. Spacecraft for Trunking System

A dual spacecraft antenna per frequency was selected to minimize feed location problems and to facilitate the use of polarization diversity coupled with frequency diversity. This simplifies the filtering requirements.

The baseline spacecraft has a communications transponder configuration (Figure 5) that filters uplinks and provides a hardwired interconnect of the 90 destination rf signals. Separate solid-state power amplifiers of 1 watt output per channel are used.

No signal processing (with associated buffer storage and special routing) is required for the baseline design. These techniques do offer improvements in overall communications efficiency, but long-term spacecraft reliability is compromised and higher data rates are not expected to be needed for the first generation system implementation.

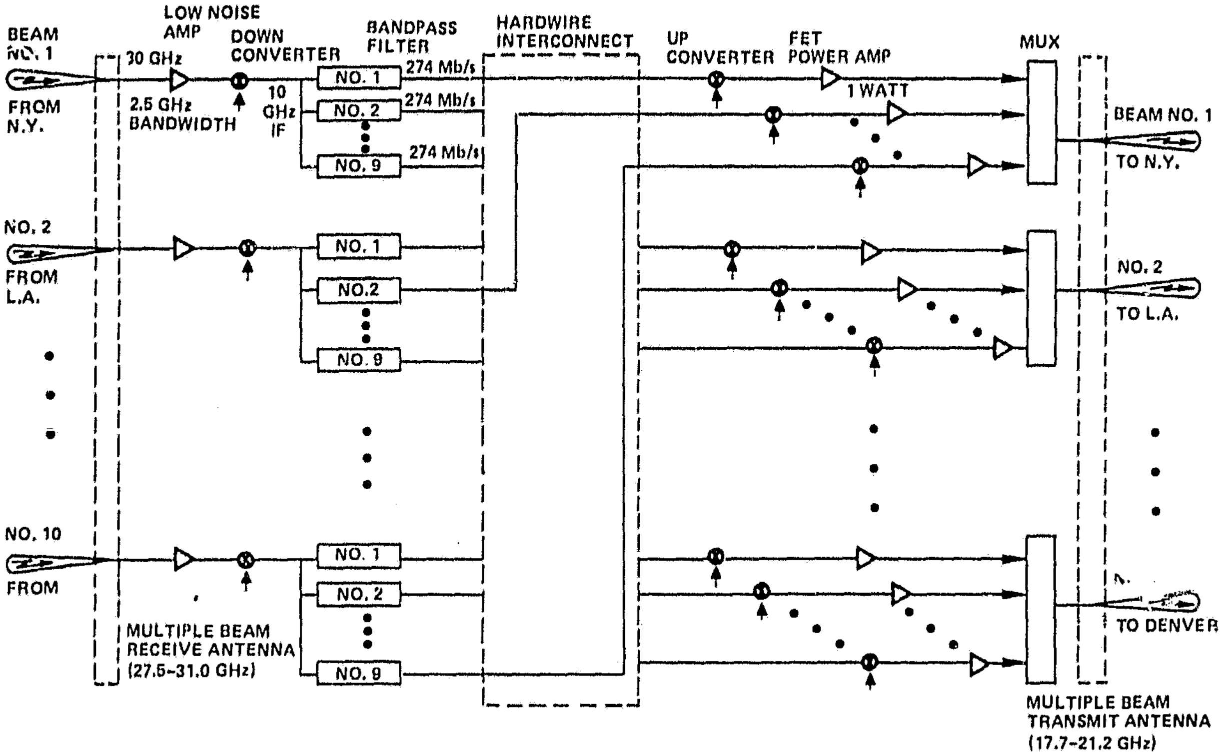


Figure 5. Communications Subsystem Configuration

Trunking Earth Terminals

The earth terminals are 12 meters in diameter, and a second diversity terminal is located at each site (with separation of 8 km or more from the main terminal) to minimize the effect of rain attenuation, as shown in Figure 6. A simplified terminal configuration is shown in Figure 7.

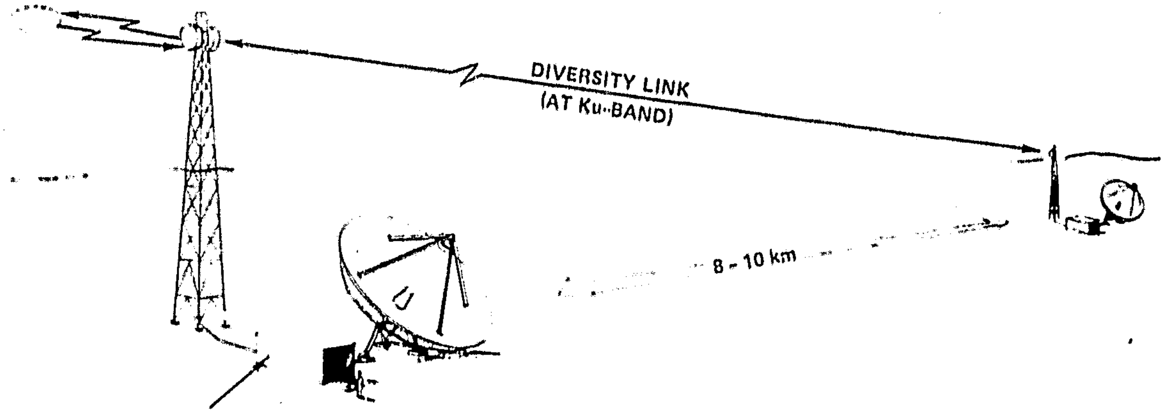


Figure 6. System Configuration of Trunking Site

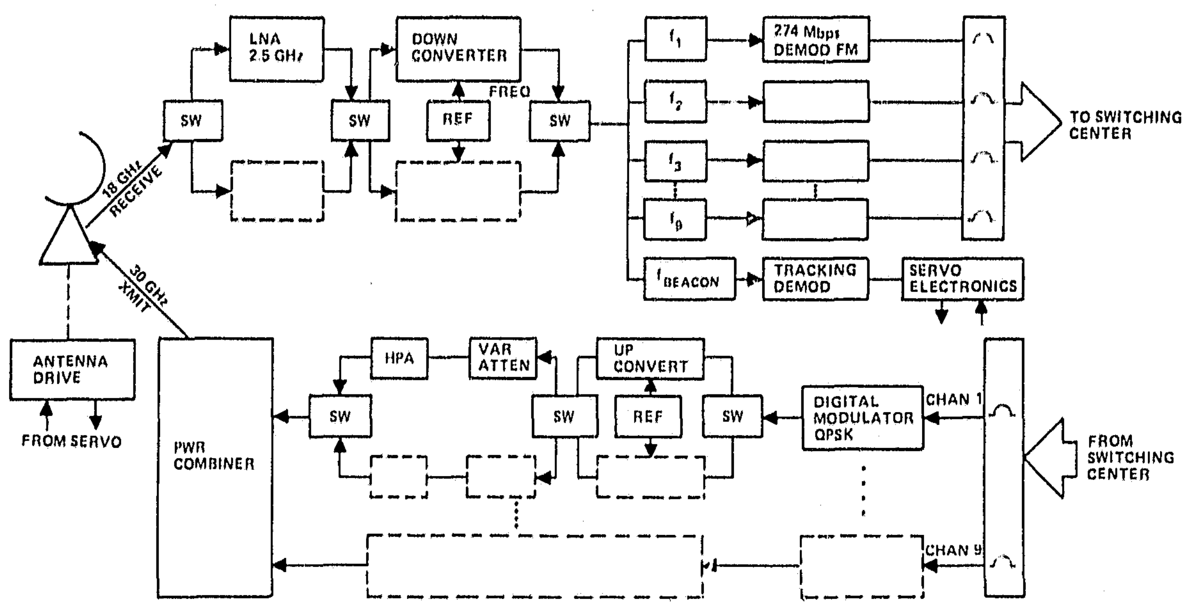


Figure 7. Trunking Terminal Configuration

Trunking Communications Links

The typical link configuration for a trunking system is shown in Figure 8. The use of 12-meter-diameter diversity earth terminals and 1 watt of satellite transmitter power per channel per beam results in net system margins that permit greater than 99.9% communications availability, as shown in Table 2.

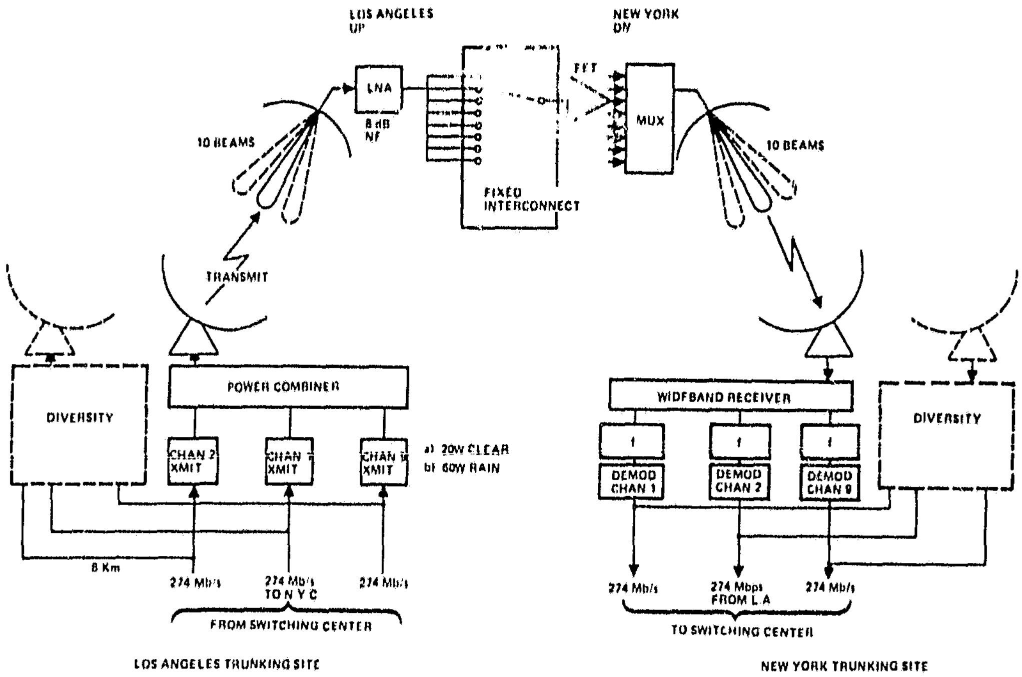


Figure 8. Baseline Link Configuration

A significant amount of signal transmission attenuation is incurred at the 18/30 GHz bands during heavy rainfall. Link margins may increase in order to minimize outage during heavy rain, but the system costs rise rapidly. The baseline trunking design provides 99.9% communications availability (ie, 9 hours outage per year) to diversity earth terminals through use of 6 dB rain margins at 18 GHz and 9 dB at 30 GHz. A communications bit error rate of 10^{-6} is assumed. Computer to computer data transfer at 10^{-7} to 10^{-9} bit error rate may be achieved by trading off bandwidth capacity for error correcting coding.

Table 2. Summary Link Budget for 274 Mb/s QPSK

	Case 1 No Rain	Case 2 Uplink Rain	Case 3 Downlink Rain
Uplink (30 GHz)			
Ground Antenna gain (12 meter dia)	+ 69.0 dB		
Transmitter power per channel	+ 13.0 dBW	+ 17.8	
Rain attenuation for 99.9% reliability	0	– 9.0	
Satellite antenna gain (12 ft dia)	+ 57.7 dB		
Uplink net C/kT	+109.2 dB-Hz	+105.0 dB-Hz	+ 109.2 dB-Hz
Downlink (18 GHz)			
Satellite Antenna gain (14 ft dia) peak	+ 54.7 dB		
Pointing loss for ± 0.1°	– 1.3 dB		
Off axis scan (± 3°) degradation	– 0.5 dB		
Transmitter power/channel/beam (1.0 W)	– 0.0 dB		
Rain attenuation for 99.9% reliability	0		– 6.0
Ground antenna gain (12 meter dia)	+ 64.9 dB		
Noise temperature	– 22.8 dB · K		– 24.8
Downlink net C/kT	+109.9 dB-Hz	+109.9 dB-Hz	+101.9 dB-Hz
Combined link			
Total up and down C/kT	+106.5 dB-Hz	+103.8	+101.2
Required system C/kT	+ 98.2 dB-Hz	+ 98.2	+ 98.2
Net system margin (With 8 km ground diversity)	+ 8.3 dB	+ 5.6 dB	+ 3.0 dB

Trunking Costs

The costs generated during the study are based on a parametric model developed by FACC, which incorporates several parametric algorithms empirically derived by FACC and a modified version of the USAF Space and Missile Systems Organization spacecraft cost model.

The baseline trunking system costs (Table 3) show that the total 10-year costs for fixed investment and operations of terminals and TT&C is expected to be $425 million. The spacecraft and launch segment make up 68% of the program costs, and earth terminal fixed and operating costs make up the balance of 32% for the condition of a 10-site network.

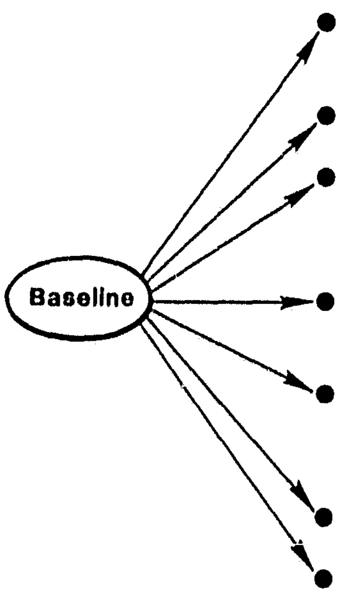
Table 3. Trunking System Baseline Configuration

Baseline Design:	25 Gb/s system capacity 10-site coverage with 0.3° antenna beams FDM with 274 Mb/s per carrier Solid-state amplifiers in spacecraft Diversity earth terminals of 12 m diameter No onboard switching or processing		
System Costs: (10 yr)	Spacecraft	$195 M	68%
	Launch and TT&C	$ 95 M	
	Earth terminals fixed	$ 78 M	32%
	Operations costs	$ 57 M	
Allocated Circuit Costs: (Satcom segment only)	Duplex 64 kb/s channel	$ 300/yr	
	Simplex 1.5 Mb/s channel	$3,600/yr	

The large fixed costs of the satellite communication (satcom) system are incurred early in the program, whereas revenue would be spread over the full operating period. After adding a cost of money it is expected that a duplex 64 kb/s channel would require $300 per year in revenue to offset the satcom costs only. A simplex 1.5 Mb/s channel would require $3600 per year. These are costs allocated per occupied bandwidth. Other costs must then be added in order to determine expected tariffs.

Alternative Trunking Systems

Figure 9 shows some of the key alternative concepts to the baseline trunking system. These alternatives include changes to the number of terminal sites, the system capacity, nonuniform channel bandwidth allocation, time division multiple access (TDMA) modulation, elimination of the diversity terminal, and increase of spacecraft power. Some of the alternatives may include combinations of parameter changes.



Increase number of sites	- Increased complexity of S/C multiplexing but tails circuit costs reduced
Increase system capacity	- User demand may not exceed 25 Gb/s for 1st generation
Nonuniform channel capacity	- Recommended for more efficient match to user needs
	- New York beam traffic limits system
TDM modulation	- High-capacity system requires 2.5 Gb/s modulators and high-peak power transmitters
Eliminate diversity terminal	- Saves $3.2 M per site but communications availability decreased or space segment costs increased significantly
Increase S/C power	- Becomes cost effective for large number of earth terminals
Collector SATCOM links within beam	- May be included to reduce tails circuit costs

Figure 9. Trunking System Alternatives

4.0 DIRECT-TO-USER SYSTEMS

The direct-to-user (DTU) satellite communications system at 18/30 GHz is designed to accommodate a large number of user earth terminals (1,000 to 10,000), which may be located anywhere within the continental United States (CONUS) excluding Alaska. The main feature of this type of configuration is that the user terrestrial network distribution costs are lower than trunking systems because of the larger number and greater geographic distribution of terminals. For DTU systems the total cost of the earth terminals generally exceeds that of the satellite segment; hence it becomes very important to optimize the performance/cost relationship for unit terminals.

The general configuration of the baseline DTU system is shown in Figure 10. A TDMA method of communications is used. Twenty-five coverage beams from a geosynchronous orbit satellite provide full coverage of CONUS (48 states) with half-power beamwidths of about 1°. The earth terminals are 4.5 m in diameter, and a quantity of 1000 is expected for a full network. To minimize cost, a diversity terminal at each site is not provided.

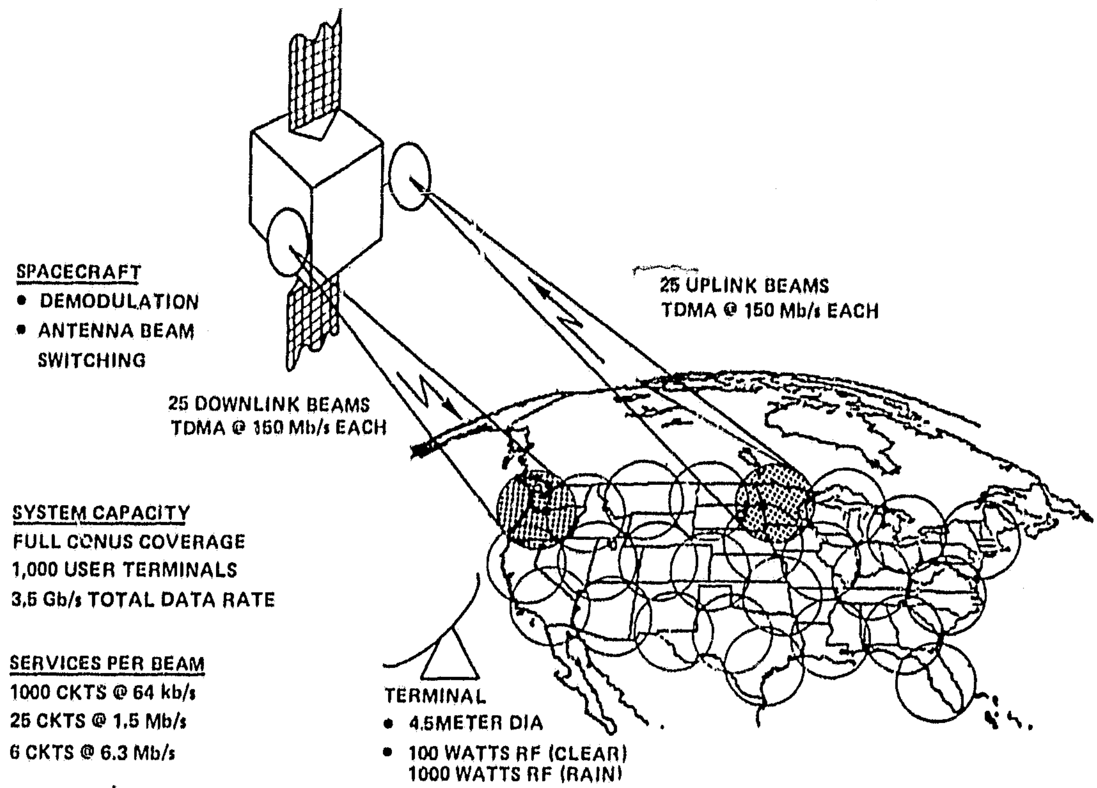


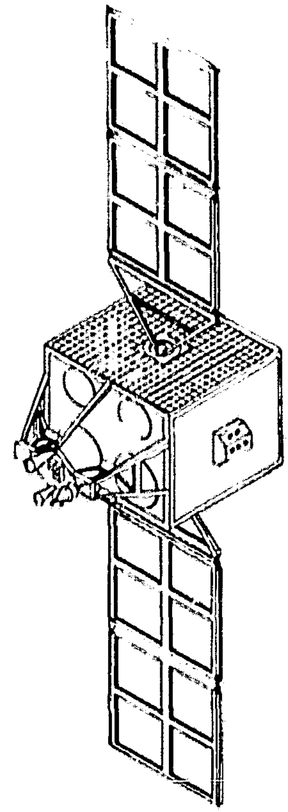
Figure 10. Direct-to-User at 18/30 GHz

DTU Spacecraft

The baseline DTU spacecraft design (Figure 11) is three-axis stabilized and uses four small reflector antennas to provide uplink and downlink coverage. Demodulation of each uplink signal is achieved, and a baseband switch operating at 750 reconfigurations per second is used to interconnect uplink and downlink antenna beams.

The spacecraft is expected to have an on-orbit weight of 2650 lb including sufficient fuel for the 10-year design lifetime. The length of the spacecraft is 15 ft and an additional 6.5 ft is required for a perigee motor. This combination would utilize about one-third of the length capacity of the Shuttle.

Solar array power of 4400 W is required at the beginning of the 10-year on-orbit life in order to support the 25 W rf communications power per beam. Twin solar paddle appendages, each about 37 ft long by 8 ft wide, would provide this power.



ON-ORBIT WEIGHT	2650 lb
LENGTH	15 ft
MAXIMUM ARRAY POWER	4.4 kW
RF POWER	25 W/BEAM
ANTENNA	25 BEAMS, 1° EACH
PERIGEE MOTOR	SPM-4
UNIT SPACECRAFT COST	$36M

Figure 11. Spacecraft for DTU System

A layout of the communications subsystem configuration for the baseline DTU system is shown in Figure 12. The odd numbered uplink beams, which have vertical polarization, would be combined and amplified with a wideband amplifier. A spacecraft noise figure of 8 dB or less may be achieved. The even numbered uplink beams, which have horizontal polarization, are received in a separate uplink spacecraft antenna. This maximizes the isolation between adjacent antenna beams.

Passband filters of 100 MHz to 200 MHz bandwidth are then used to isolate the 150 Mb/s modulated uplink signals received from each uplink beam. Individual channel demodulators are used to obtain the 150 Mb/s baseband burst rate per beam. The signals are passed to a data register so that the last 25% of each communications interbeam data block may be routed and switched separately. This is the 6.3 Mb/s wideband data, which is limited to a maximum of six uplink transmissions and six downlink transmissions per beam. Command control may be employed in order to control the routing and network configuration of the wideband data. It is possible to have a single uplink communicate to all 25 of the downlink beams simultaneously; however, this would use one-sixth of the total system wideband capacity.

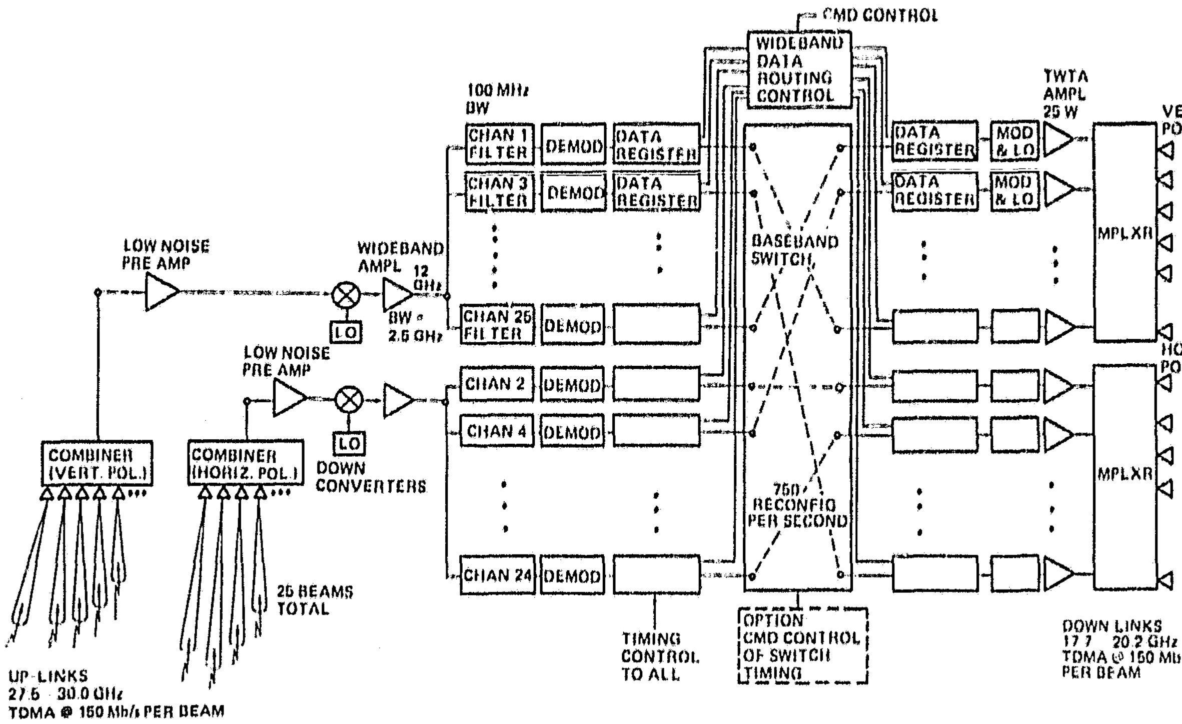


Figure 12. DTU Communications Subsystem

DTU Earth Terminals

The baseline DTU earth terminals (Figure 13) are 4.5 meters in diameter and no diversity terminal is provided. However, informal cooperation among users within a beam could be used to permit key data to be received with high reliability during heavy rainfall periods. As shown in Figure 14, the transmitter power per channel is 100 W in the normal mode and increases in steps up to 1000 W during rainstorm periods. It is expected that a network of 1,000 to 10,000 user terminals would be deployed throughout CONUS.

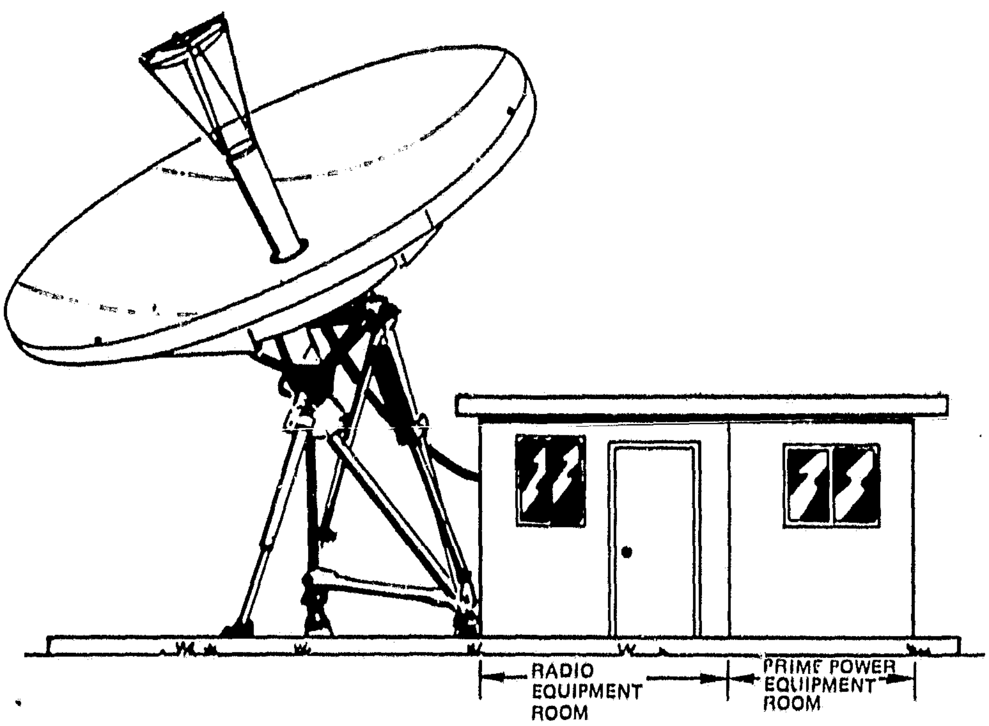


Figure 13. DTU Earth Terminal Installation

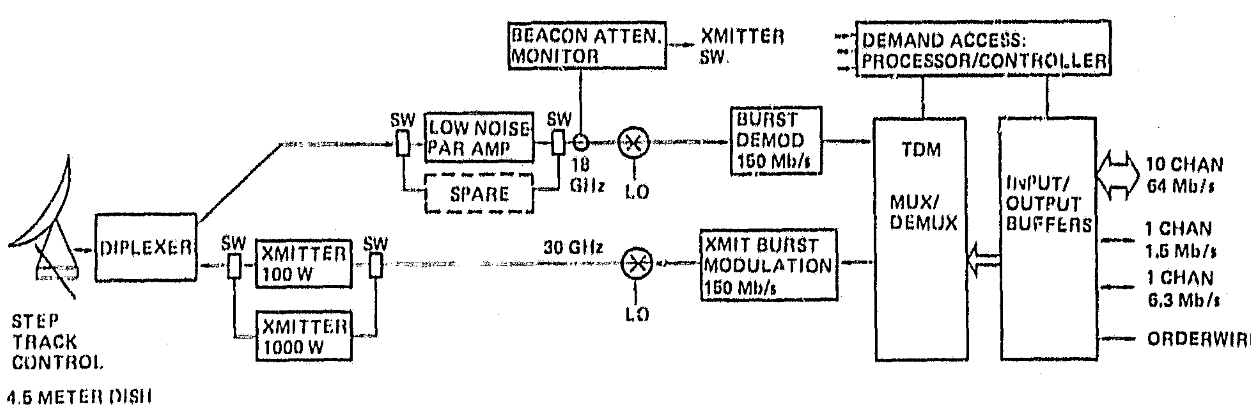


Figure 14. Standard DTU Terminal Configuration

Figure 15 shows one method for accommodating a large number of user terminals in a TDMA format. The spacecraft transponder demodulates the uplink data stream from a particular beam coverage area, for example, beam 4. The 140 Mb/s data rate is broken into intervals of time, which for this example are 1/750 second. For this period, the uplink from beam 4 is connected to one downlink antenna by means of a baseband switch. About 186,000 bits of information are transmitted during a particular interconnect.

The spacecraft baseband switch is operated at a rate of 750 antenna pair reconfigurations per second. A 10 μs guard time is established between blocks of area paired data to permit time for the switching and margin for system timing error. The baseline frame format switches through all of the 25 beam area destinations within 1/30 second and then repeats the cycle. Thus, if a voice circuit is digitized to 64 kb/s, then a block of about 2100 bits plus preamble may be sent 30 times per second from a terminal within beam 4 (for example) to a selected destination beam area. The channel assignment within the TDMA frame format may be achieved by preassigned time slots or by a controlled demand access or by a combination of methods.

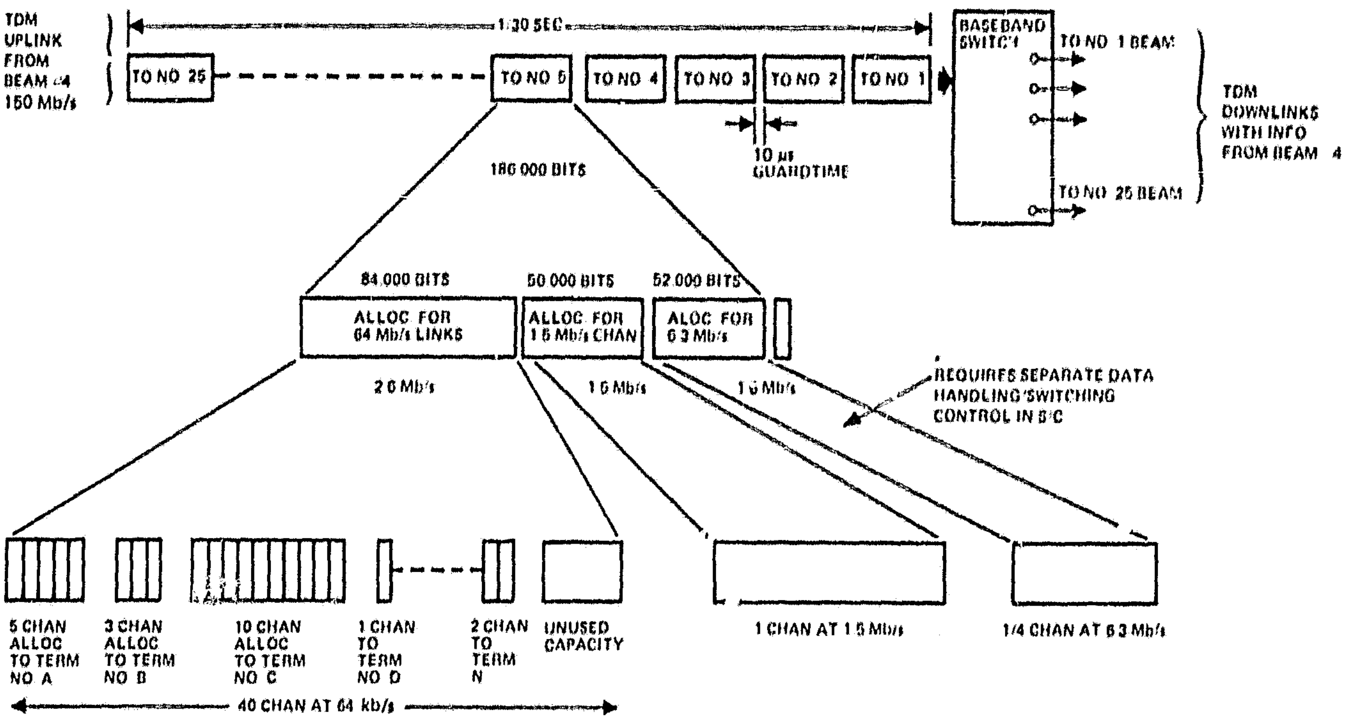


Figure 15. TDMA Frame Format

DTU Communications Links

The configuration of a satcom communications link for DTU application using TDMA is shown in Figure 16. A transmit terminal obtains a time slot (fixed-assigned or demand-access via orderwire to communications control center) for transmittal of a selected data rate to a selected terminal located within one of the 25 downlink coverage areas. The composite blocks of data are transmitted within precisely controlled time intervals at a burst transmission rate of 150 Mb/s.

The spacecraft receives the signal within the 27.5 to 30 GHz transmission band, amplifies it, and demodulates it. A baseband switch connects the originating signal to a downlink circuit for 1/750 second (as part of a cycle interconnect pattern). The baseband signal is modulated, translated to a nominal 18 GHz downlink frequency, amplified with a 25 W rf TWTA and directed to one of the 25 downlink antenna beams. The receiving terminal monitors all transmissions on the downlink within a given coverage area and identifies the preamble data signifying those transmission bursts for the selected receiving terminal.

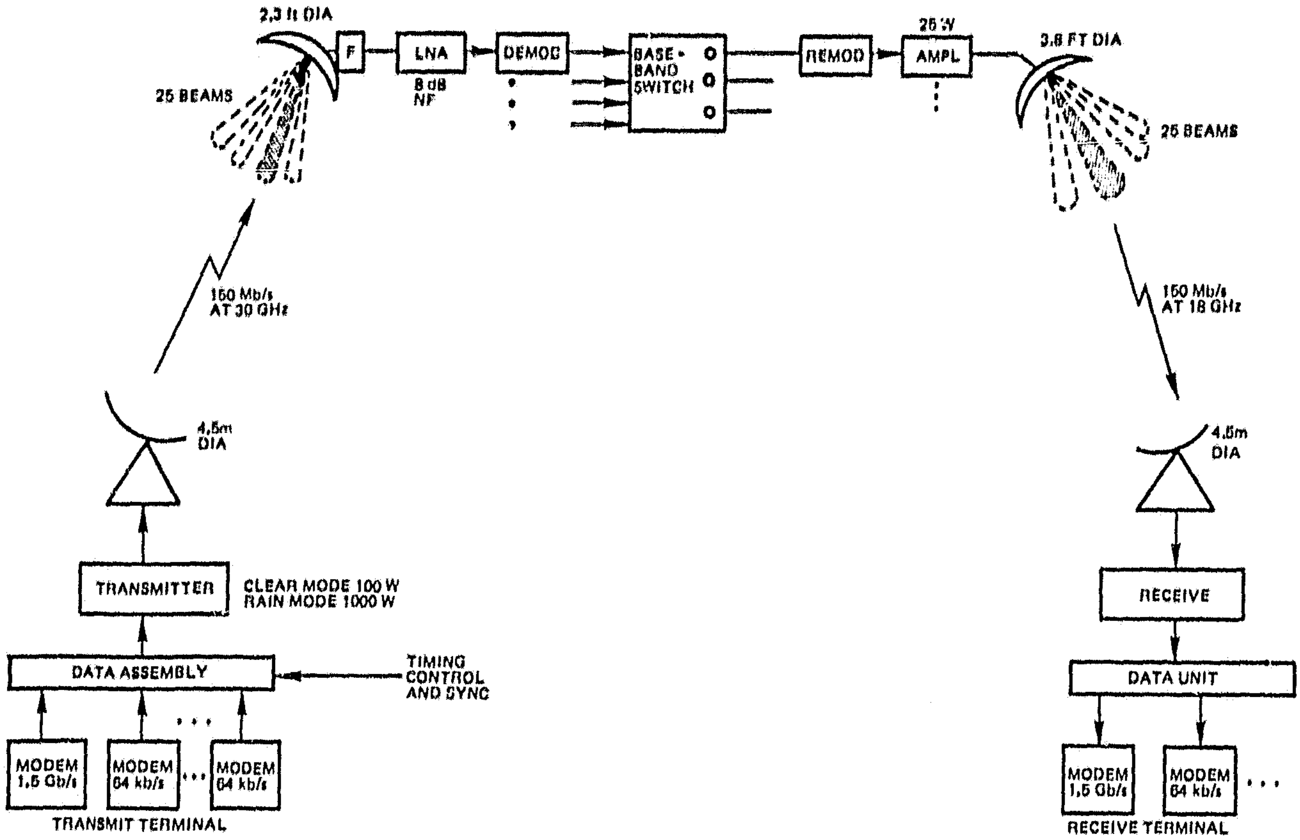


Figure 16. DTU Link Configuration

A summary link budget is given in Table 4. One of the key factors affecting link design is the margin to accommodate rain attenuation. It is expected that 95% of the terminal locations within CONUS can have 10^{-5} bit error rate data quality for 99.5% of the time if the uplink rain margin is 15 dB and the downlink margin is 5 dB. These values apply to single antenna configurations. The margins can be considerably reduced if dual earth terminal site diversity is provided.

Table 4. Summary Link Budget for 150 Mb/s QPSK

Item	Case 1 No Rain	Case 2 Uplink Rain	Case 3 Downlink Rain
Uplink (30 GHz):			
Ground antenna (4.5 m dia)	+ 60.4 dB		
Transmitter power per channel	+ 20.0 dBW	+ 29.0	
Rain attenuation for 99.5% availability	0.0	- 15.0	
Satellite antenna gain (2.3 ft dia) at EOC	+ 41.2 dB		
Uplink Net C/kT	+ 98.4 dB-Hz	+ 92.4	+98.4
Downlink (18 GHz):			
Satellite antenna gain (3.8 ft dia) at EOC	+ 41.2		
Transmitter power/beam (25 W)	+ 14.0 dBW		
Rain attenuation for 99.5% availability	0.0 dB		- 5.0 dB
Ground antenna gain (4.5 m dia)	+ 57.0 dB		
Noise temperature	- 24.8 dB-K		-26.2
Downlink Net C/kT	+101.1 dB-Hz	+102.1	+95.7
Combined Link: @10^{-6} BER			
Uplink margin	+ 3.7 dB	2.3 dB	+ 3.7 dB
Downlink margin	+ 7.4 dB	+ 7.4 dB	+ 1.0 dB
Net link performance	$\approx 10^{-9}$ BER	$\approx 10^{-4}$ BER	$\approx 10^{-6}$ BER

DTU Costs

The baseline DTU system costs are shown in Table 5. The total 10-year costs for fixed investment and operations of terminals and TT&C is expected to be $1.23 billion. The spacecraft and launch segment makes up 27% of the program costs with earth terminal fixed and operating costs making up the balance of 73% for the condition of a 1000-terminal network.

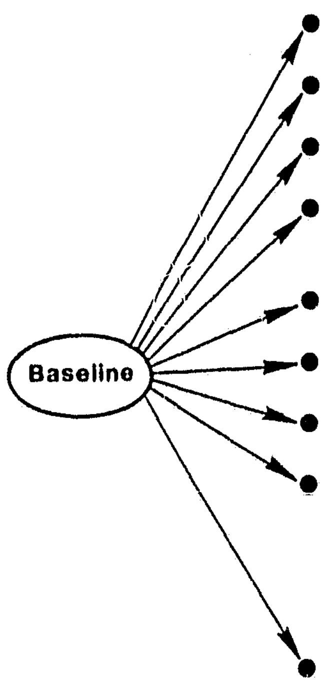
The large fixed costs of the satcom system are incurred early in the program, whereas revenue would be spread over the full operating period. After adding a cost of money it is expected that a duplex 64 kb/s channel would require $7500 per year in revenue to offset the satcom cost. A simplex 1.5 Mb/s channel would require $87,000 per year. These costs are allocated per occupied bandwidth. It is to be noted that these costs are not the expected tariffs, which must include other cost factors.

Table 5. Direct-to-User Baseline Configuration

Configuration:	3.5 Gb/s maximum capacity		
	25 beam full CONUS coverage		
	TDM @ 150 Mb/s per beam		
	Remodulation & antenna switching in spacecraft		
	1000 earth terminals of 4.5 m diameter		
System Costs:	Spacecraft	$248 M	27%
	Launch and TT&C	$ 85 M	
	Earth terminals fixed	$522 M	73%
	Earth terminals operations	$376 M	
Allocated Circuit Costs:	Duplex 64 kb/s channel	$ 7,500/yr	
	Simplex 1.5 Mb/s channel	$ 87,000/yr	
	Simplex 6.3 Mb/s channel	$365,000/yr	

Alternative DTU Systems

Figure 17 shows some of the key alternative concepts to the baseline DTU system. These alteratives include changes to the number of terminals, the system capacity, nonuniform bandwidth allocation per beam, FDMA modulation, use of onboard processing, and increased spacecraft power. Some of the alternatives may include combinations of several parameter changes.



Increase number of terminals	- Service availability decreases
Increase spacecraft power	- Small impact because of uplink limitations
Increase system capacity	- Earth terminal diameter exceeds 5 meters - too large
Allocate extra channels to high-traffic beams	- Should be incorporated for balanced system, increases switching matrix complexity
Skewed data capacity among beams	- Feasible with variable switching dwell period
Increase number of beams	- Switching matrix becomes excessive
Include onboard processing	- Efficient - however, reliability compromised, 2nd generation
FDM modulation	- Eliminates spacecraft switching – however, filters become excessive for large numbers of links - Earth terminal transmitter power reduced, but frequency synthesizer added
Decrease communications link availability	- Eliminate 5 dB down/15 dB up rain margin - reduces system cost

Figure 17. DTU Alternatives

5.0 LINK AVAILABILITY

High availability of communications links is an important requirement today and will become even more important in the future. Some transmissions such as facsimile, electronic mail, and batch processing data communications can be buffered and would not greatly suffer from rain outages. Other services, for which any outages are considered to be inconvenient and undesirable, include person-to-person communications.

On an average basis a given location within CONUS is expected to be receiving measurable amounts of rain about 1.5% of the time. During periods of heavy rainfall the satcom signal transmission at 18 GHz and 30 GHz frequency bands will incur a significant attenuation. It is desired to keep the satellite and earth terminal performance parameters low in order to minimize cost; however, the resulting system propagation reliability must be matched to user requirements. A proper understanding of the 18/30 GHz rainfall attenuation effects is therefore one of the most important elements in the determination of viable satcom system configurations.

The location of the earth terminal within CONUS has a major effect on communications availability. One grouping of equivalent climatological zones is shown in Figure 18. The worst case region, zone 5, includes the gulf areas of southeast CONUS where the average rainfall is 64 inches per year and 50% of the rain occurs by thunderstorm. A single site terminal rain margin of 7 dB is required at 18 GHz and 17 dB at 30 GHz to achieve 99.5% communications availability.

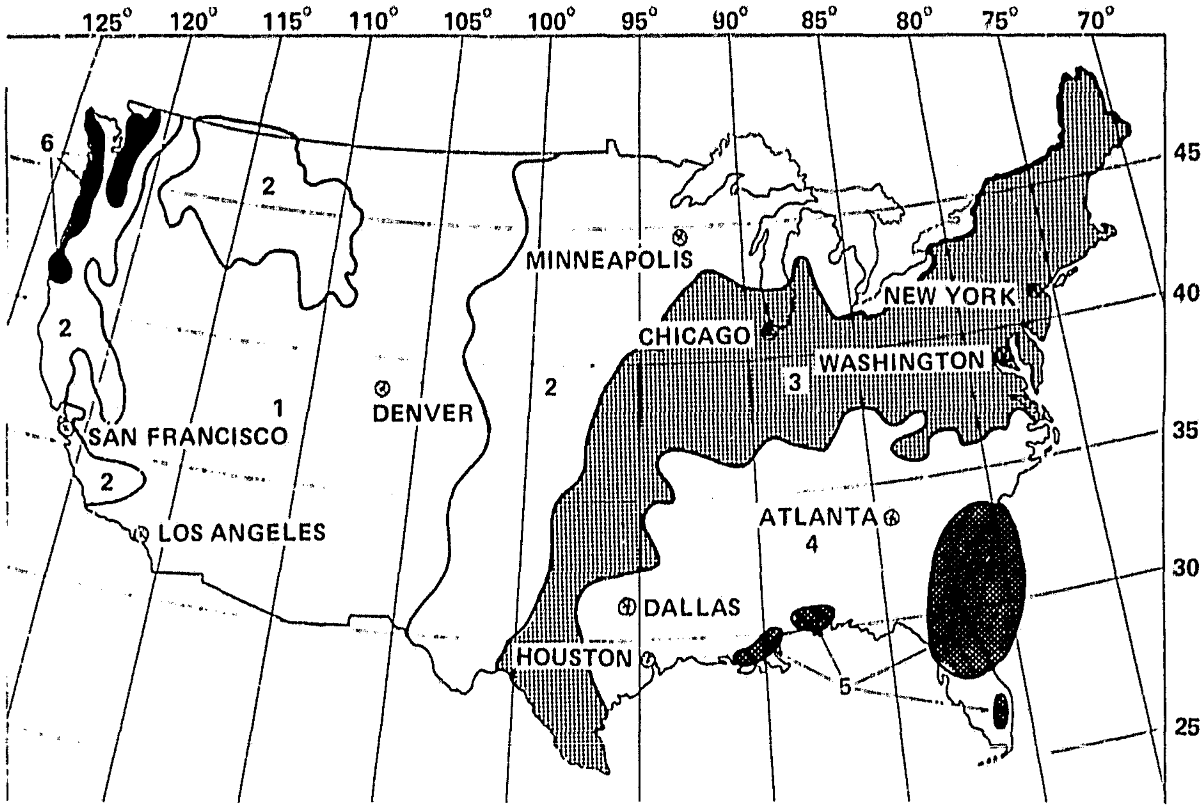


Figure 18. Climatological Zones for CONUS

High Communications Availability

The communications user is interested in overall end-to-end availability. Propagation outages are only one source of possible disruptions. Other outages are possible due to equipment failure. It is believed that the following communications availabilities will be desired as a high performance goal.

High volume trunking earth stations	99.99%
Direct-to-user earth stations	99.9%

Analysis of rain attenuation for this report was prepared by Future Systems Incorporated (FSI) under subcontract to Ford Aerospace & Communications Corporation (FACC). The FSI assessment of uplink and downlink margins that will be needed for high performance communications availability in each of the previously identified rain zones is given in Table 6. It is shown that diversity terminal configurations will considerably reduce link margins; however, total terminal costs are almost doubled.

Table 6. Required Uplink and Downlink Margins (in Decibels) for High Availability Services

Station		Rain Zones					
		1	2	3	4	5	6
Trunking (at 99.99% availability)							
No diversity	downlink	13	23	35	49	54	28
	uplink	36	66	86	111	121	75
With diversity	downlink	6	6	6	7	7	6
	uplink	8	9	10	10	11	9
Direct-to-User (at 99.9% availability)							
No diversity	downlink	4	7	8	13	19	10
	uplink	13	17	24	38	50	26
With diversity	downlink	4	5	5	6	6	6
	uplink	8	8	8	9	9	8

Notes: 1 Propagation margins above 10 dB are undesirable and those above 20 dB are probably impractical.

Low Cost Systems

A significant reduction in costs could well induce some users to accept a lower availability for certain types of service. For such services the following availabilities would be appropriate:

At trunking earth stations	99.9%
At direct-to-user stations	99.5%

The corresponding uplink and downlink margins are then reduced to the values listed in Table 7.

Table 7. Required Uplink and Downlink Margins (in Decibels) for Reduced Availability Services

Station		Rain Zones					
		1	2	3	4	5	6
Trunking (at 99.9% availability)							
No diversity	downlink	4	7	8	13	19	10
	uplink	13	17	24	38	50	26
With diversity	downlink	4	5	5	6	6	6
	uplink	8	8	8	9	9	8
Direct-to-User (at 99.5% availability)							
No diversity	downlink	3	3	4	5	7	5
	uplink	7	8	11	14	17	16
With diversity	downlink	3	4	4	5	5	5
	uplink	7	7	8	8	8	8

Notes: 1. Propagation margins above 10 dB are undesirable and those above 20 dB are probably impractical.

Hybrid Systems

Another technique for achieving high availability is to incorporate several frequency transmission bands within the same spacecraft. The lower frequency bands (4/6 GHz and 11/14 GHz) are less affected by rain attenuation and could be used for those users requiring real time information or high quality data without interrupt. The 18/30 GHz transmission band (with its associated wideband capacity) could be used during clear weather operations or for bulk data transfer, which is not affected by short periods of interrupt.

6.0 TECHNOLOGY ASSESSMENT

A major study objective was to identify key technology that will be required to support the various 18/30 GHz satcom system configurations. Some of the equipment has already been developed on other programs, some requires modifications to current equipment, and some requires new development and qualification.

It is not expected that the technology development will present a major hurdle to a successful first generation 18/30 GHz satellite data system. As the user needs become greater for subsequent operational periods, then more of the exotic high technology requirements will be required. The Japanese have already launched an experimental 18/30 GHz communications satellite (CS) which has six channels of 100 Mb/s each. It was placed in synchronous orbit in December of 1977 and continues to operate satisfactorily.

Key Technology for First Generation System

The key technology developments identified for support of baseline FDMA trunking systems at 18/30 GHz are listed in Table 8. The critical items include a multiple beam spacecraft antenna with half power beamwidth of 0.3° or less. Good isolation between beams is required; hence low sidelobe techniques coupled with polarization diversity may be employed. The spacecraft ower amplifier is required to have long term reliability and to provide about 1 to 5 W rf output from solid state devices. Low-loss multiplexer combiner techniques will be required. The spacecraft digital data handling system must accommodate baseband digital data rates of up to 274 Mb/s with QPSK modulation. A space diversity earth terminal is required; hence techniques for maintaining bit integrity during switchover between terminals should be developed. The control of earth terminal transmitter power output level during rain conditions should also be examined.

Table 8. Trunking Technology for First Generation System

S/C Antenna:	-	Multiple spot beams of 0.3° beamwidth
	-	Low sidelobe/polarization diversity for isolation
S/C Power Amplifier:	-	Solid state with 1 to 5 watt RF output at 18 GHz
	-	Low-loss RF multiplexer
S/C Data Handling:	-	Channel equalization at 274 Mb/s
	-	25 Gb/s thruput capacity
Earth Terminal:	-	Diversity switching techniques for bit integrity
	-	High-speed modems

The key technology developments identified for support of baseline TDMA DTU systems at 18/30 GHz are listed in Table 9. The critical items include a multiple beam satellite antenna for full CONUS coverage, a new satellite power amplifier with 25 to 100 W output at 18 GHz, demodulation/remodulation equipment suitable for satellite use, and a K_A-band nd user terminal that can be produced in quantity at low cost.

Table 9. DTU Technology for First Generation System

S/C Antenna:	- Overlapping multiple beams for full CONUS coverage - Feed layout, beam control, polarization diversity
S/C Power Amplifier:	- 25 to 100 watts RF per beam at 18 GHz - Multichannel
S/C Data Handling:	- High reliability/redundancy - Demodulation/remodulation - Baseband switching matrix
User Terminals:	- Low-cost power amplifiers at 30 GHz, variable power control - Low-cost autotracking and timing - Low-cost manufacturing/checkout techniques - Unattended operation

The cost of the user terminals is a major factor affecting the viability of the DTU concept. Use of existing technology leads to a unit procurement cost of $400,000 to $600,000 per terminal. Clearly, the requirement exists for development of new technology that can lead to substantial cost reductions in ground terminal components. Reduction of operational and maintenance costs is also a significant factor in the overall DTU system costs. Methods for achieving reliable operation with unattended operation and an acceptable MTBF need to be considered.

Key Technology for Advanced Follow-on Systems

The following additional technology developments have been identified to improve system capacity and reduce costs for second generation systems:

a. Variable satellite transmitter power
b. Onboard signal processing
   1. Multiple carrier demodulation
   2. Store and forward
   3. Cross-connect of DTU and trunking circuits
c. Dual frequency band antennas with smaller spot beam
d. High peak power/low duty cycle amplifiers for low-cost earth terminals

A technique for efficiently varying the satellite transmitter power would allow matching the individual satellite channel capacities to the instantaneous traffic load and required rain attenuation margin, thereby increasing total satellite throughput.

The use of advanced signal processing techniques on the satellite would allow optimizing the uplinks and downlinks separately. Work performed under a separate study of store-and-forward system techniques indicates potential gains in store-and-forward processing for burst (packet) type traffic.

Any dual-frequency band concept would require development of low-cost dual-frequency feeds for the ground terminal antenna and possibly for the satellite also. The Japanese CS satellite used a dual frequency C-band and K_A-band satellite antenna.

Finally, for the direct-to-user terminal operating in a TDMA mode, the need exists for a low-cost high-power amplifier capable of delivering high peak powers with low duty cycle bursts of carrier at 30 GHz.

Experimental Flight Test Program

To reduce the risk of new technology on an operational 18/30 GHz satcom system, it is recommended that key items be evaluated through an experimental flight test program. Specific technology items would be identified after completion of a user demand/concept analysis phase. In order to obtain full benefits of a test program, it is important to initiate detailed planning of tests as early as possible.